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Review

Overcoming Food Security Challenges within an Energy/Water/Food Nexus (EWFN) Approach

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Abstract: The challenge of feeding nine billion people by 2050, in a context of constrained resources and growing environmental pressures posed by current food production methods on one side, and changing lifestyles and consequent shifts in dietary patterns on the other, exacerbated by the effects of climate change, has been defined as one of the biggest challenges of the 21st century. The first step to achieve food security is to find a balance between the growing demand for food, and the limited production capacity. In order to do this three main pathways have been identified: employing sustainable production methods in agriculture, changing diets, and reducing waste in all stages of the food chain. The application of an energy, water and food nexus (EWFN) approach, which takes into account the interactions and connections between these three resources, and the synergies and trade-offs that arise from the way they are managed, is a prerequisite for the correct application of these pathways. This work discusses how Life Cycle Assessment (LCA) might be applicable for creating the evidence-base to foster such desired shifts in food production and consumption patterns.

Keywords: food security; energy/water/food nexus; LCA

1. Introduction

During the World Food Summit [1], food security was defined as a situation "when all people at all times have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life". This definition stressed the importance of elements that go beyond the availability of food which are: access (individual entitlement for obtaining food), food safety and nutritious value, and stability through time.

In the last century the primary focus has been on enhancing food productivity and during the "Green Revolution" (1966–1985) research and technological improvements led to significant increases in yields, which meant that overall global production kept ahead of the overall demand [2]. These increased yields were mainly achieved due to radical improvements in the use of fertilizers, pesticides, agricultural machinery, and irrigation systems (therefore greater use of water). However, this was accompanied with higher resource intensity and an increased reliance on oil (in fertilizer production).

Between 1990 and 2010 the production of food (+56%) grew at a faster rate than the world population (+30%) and yet significant inequalities now exist with regard to access [3,4]. For example, whilst in 2008 an estimated two billion people worldwide were overweight or obese [4,5], in 2011–2013 the Food and Agriculture Organization of the United Stations (FAO) [4] estimated that 842 million people suffered chronic undernourishment. In addition this "bottom billion", as they are referred to, had little access to clean water and energy.

Current food production systems that include greenhouse gas intensive food products, in developed and developing countries, continue to deplete natural resources and pollute ecosystems at a rate that is unsustainable and this will compromise the capacity for nations to produce food for future generations. Ultimately in a context of a world of limited resources exacerbated by the effects of climate change (and associated mitigation and adaptation requirements), the achievement of food security is one of the biggest challenges of the 21st century [6]. This is important when we consider that in future decades it is expected that further pressures will be applied as a consequence of: growing population (expected to reach nine billion people by 2050), urbanization (urban populations expected to double by 2050), economic growth and consequent changing lifestyles. Each of these will cause an increase in demand for water (estimated to increase by 40% by 2030), energy (estimated to increase by more than 40% by 2030) and land [3,4].

A new approach to food security is required that does not compromise biodiversity and ecosystem services and reduces the impact on climate change [7], which moves the attention from availability to access, and from calories to nutrients, enriched with a view towards the future (rather than just considering the present needs). Such a radical change to the food system should deliver better nutritional outcomes at less environmental cost, and in order to do so it is necessary to abandon conventional silo thinking by breaking down the barriers between disciplines [6,8]. In response to these challenges food security and related research is transitioning to adopt a much broader perspective than food productivity alone [9]. This includes improving insights into the interconnectedness between energy, water and food systems and the surrounding environment (the so-called nexus approach) which underpin future strategic options and pathways with respect to food security [10]. In this article, it is argued how such a radical change can be fostered by assessing the environmental sustainability of food systems through the tool of Life Cycle Assessment (LCA). This has emerged in the last two decades as the leading methodology to quantify the environmental impact of products thanks to its overarching approach, which includes all stages of the life cycle of a product, and a wide range of impact categories [11].

Within this paper, EWFN (Energy Water Food Nexus) is presented as a valuable approach to achieving food security with a particular focus on sustainably balancing the growing demand for food with the constrained production capacity enabling supply streams. The methodology adopted is outlined in Section 2. Section 3 defines clearly the nexus issues between Energy, Water and Food highlighting points of concern (*i.e.*, factors causing pressure points on their respective supply systems) and ways of achieving more sustainable solutions through a EWFN approach. Three key pathways to overcoming the food security challenge are highlighted (Section 4) and the role of LCA as a facilitating tool in each is outlined (Section 5). A discussion is given in Section 6 and conclusions drawn in Section 7.

2. Methodology

The methodology is formed of three stages as illustrated in Figure 1.

The first stage (Section 3) is a review of existing literature on the nexus between water, energy and food and an investigation into its role within the food security challenge which has been defined as:

> *"the challenge of feeding an overgrowing population in a context of constrained resources and changing climate."*

Therein, the nexus is defined, key drivers of pressure for security of these three resources are identified and within this context the overarching aim of EWFN is outlined.

The second stage (Section 4) identifies the key pathways suggested within the literature that can be adopted to achieve a balance between the growing demand for food taking into consideration constrained production capacity. Explanation is provided as to why all of them are aligned with the EWFN approach.

The third stage (Section 5) identifies whether LCA is the appropriate tool to create the required shifts in production and consumption practices identified in Stage 2. In this stage, the literature was critically reviewed to identify existing publications showing how this tool can be applied to foster decisions in line with that specific pathway. The result was the identification of five main types of studies of interest, differentiated according to their main goal. For each of them an analysis of the applicable instruments, involved stakeholders and methodological choices is provided together with a number of examples of publications.

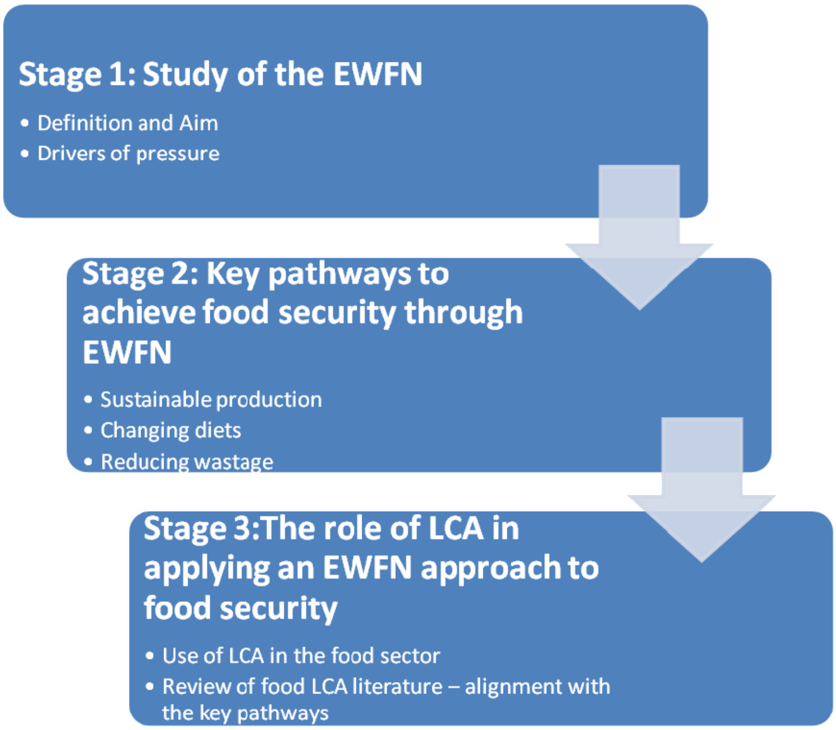

Figure 1. Graphical elaboration of the methodology.

3. Stage 1: The Nexus between Energy, Water and Food Security

3.1. Definition and Aim

The word "nexus" derives from the Latin verb *nectere* which means "to connect", and expresses the study of the interactions and connections between two or more things, often termed dependencies or interdependencies. The water, energy and food nexus (EWFN) is therefore the study of the interactions between these three resources, the synergies and trade-offs that arise from the way they are managed, and the potential areas of conflict. This approach is based on the idea that it is not possible to address water, energy or food security in isolation in an effective way without considering the implications on the other two, in other words the broader consequences caused by the interdependencies between them [10,12,13]. For example, the basis of food production requires water directly to grow crops, and this water usually requires pumping and treating which requires energy; in turn electricity production is dependent on water for cooling and steam generation. Energy and water are further required for processing, packaging, transport and storage, preparation from the end-user and ultimately final disposal of food. The use of energy in each phase of the food chain, for the case of the UK, is illustrated in Figure 2.

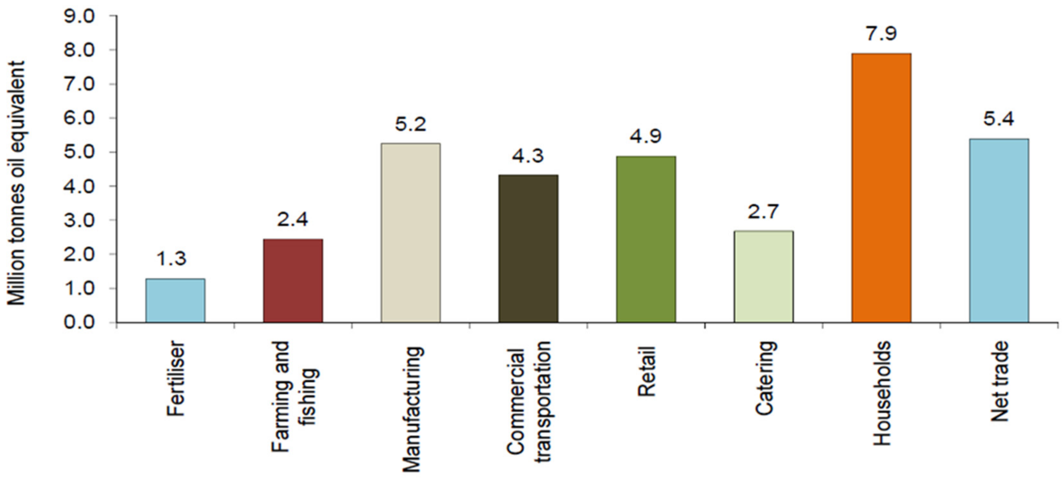

Figure 2. Energy use in the UK food supply chain [14].

Figure 3 shows just how closely interconnected the elements of the nexus are by showing the correlation between food and energy prices. This close connection is a consequence of the reliance of modern agriculture on fossil fuels and of first generation bio-fuel expansion, which has made energy and food production become competitors for land and water [10,12,15]. This tension between energy and food represents a case in which a trade-off can be made considering all aspects of the nexus.

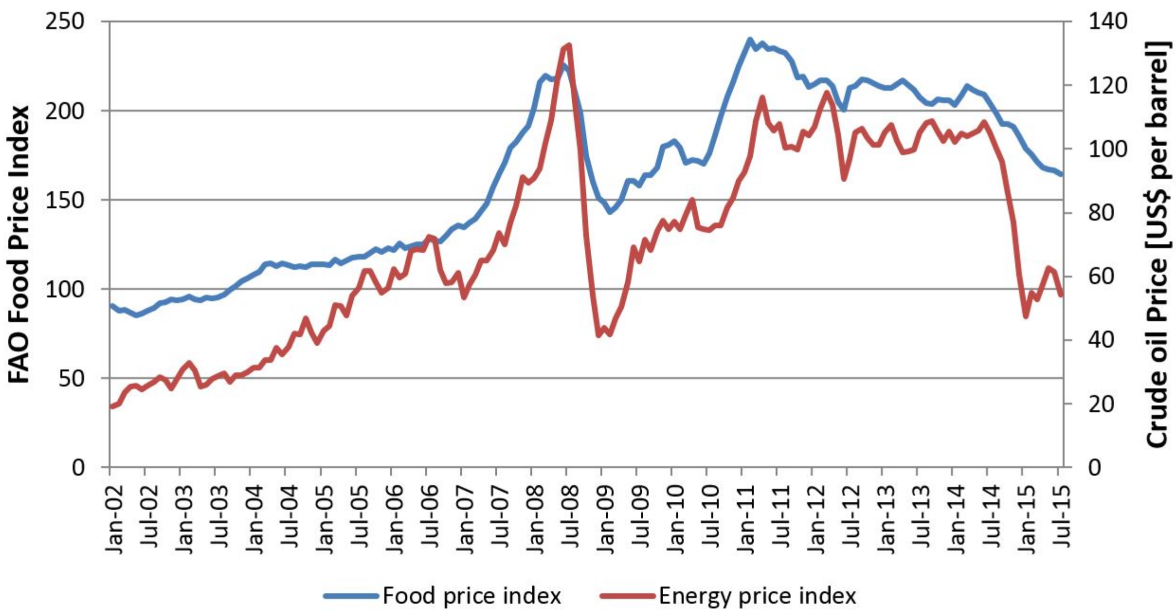

Figure 3. World food and oil prices. January 2002 to July 2015 [16,17].

The ultimate goal for analysing the connections between water, energy and food, and highlighting the potential areas for conflict, trade-offs and synergies, is to guide policy-making towards integrated solutions and approaches to resource use [12,13,18–20]. For example, a EWFN approach can dismantle the logical basis of policies that, in order to ensure food security, heavily subsidize electricity for pumping ground water for irrigation. A number of examples from the past show how this often led to over-exploitation of groundwater, therefore to water insecurity, which in the long term can compromise food security itself [12,13,21]. Furthermore, the removal of subsidies can not only cause a decline in electricity consumption but also a recovery in groundwater levels: this is a clear example of synergy between water and energy identified by the nexus approach [13].

The water, energy and food nexus has been identified as one of the three greatest threats to global economy [22]. It has also been defined a "security" nexus, as access to all three elements must be ensured in order to have prosperity and peace [18]. Both of these matters further emphasize the importance of achieving this result.

3.2. Drivers of Pressure on Resources

The main factors that put pressure on food security, in the context of an EWFN approach are [10,13,23–28]:

- Urbanization
- Population growth
- Increasing living standards
- Climate change
- Globalization (where externalities of supply are "hidden")
- Political instability

A combination of economic growth, globalization and urbanization has a negative impact on the Earth's natural ecosystem and on resource availability. For example, as people move to more developed cities in general their lifestyles change, in particular by eating more meat and other water and carbon intense products. (Beef cattle has an average water footprint of 15,400 m^3/ton, [29], and a carbon footprint (average value for England, according to the PAS 2050 methodology) of 12.65 kg CO_2e/kg (live weight), [30]). Moreover, modern city dwellers have expectations for food to be available all year round (as a consequence of a loss of contact with natural rhythms and seasonality of products). This loss of connection with the natural component of food production, typical of city dwellers, has also caused a stronger tendency to waste food, which implies the waste of water and energy that were involved in the production, processing and distribution requirements [10,13]. Furthermore the geographical displacement of consumption (from production through farming and home growing) has meant that food wastage is no longer used as a resource for animal feed or compost and has become an undesirable output that has to be disposed of in a sustainable manner. (A more detailed analysis of the causes of food wastage along the food chain is provided in Section 4.3).

Increasing living standards in developing countries and consequent changing lifestyles are considered to be causing a global transition towards less environmentally sustainable diets, rich in meat, processed foods, refined sugars, refined fats, and oils [7,13,27,28]. Figure 4 illustrates this trend, showing a correlation between income and per capita meat consumption for the year 2002, and comparing it with the total meat consumption of the United States and China (where the latter in the same year was already consuming significantly more meat than the former even though the per capita consumption was lower and expected to keep growing).

In addition climate change, which is contributed to significantly by energy use and food production, is adding further pressures on water supplies and agricultural productivity. This is a consequence of rising temperatures, significant changes to normal weather patterns that potentially influence crop yields, rising seawater levels, shrinking glaciers and increase in extreme weather events, like droughts and floods. Producing and processing food accounts for 14% energy consumption by UK businesses, [3,31,32], while an analysis from the European Commission [33] finds that food accounts for 31% of the total E-25 greenhouse gases emission. In addition, climate change mitigation measures can put further stress on key elements of the nexus, for example in the case of water- and land-intensive practices for carbon sequestration or measures for reducing the carbon emissions, such as intensive bio-fuels cultivation [13].

Global food trade has the (sometimes negative) consequence of giving the opportunity to externalize to other countries resource extraction and waste production, and of generating geo-political tensions when "outsourcing" reliance on other countries for fundamental, crucial resource supply streams [34]. However, such an approach has the positive potential for improving resilience of a food supply network/web, through giving a variety of alternative multi-nodal sources to address local scarcities (addressing localized drought or disease issues), and for increasing the overall resource use efficiency, if trade is assumed to follow productivity gradients [13,35–37]. For instance, a country that has low availability of water, through choosing to import water-intensive food products from another country that has unfettered access to blue (surface and groundwater), green (rainwater) and grey water (polluted freshwater), rather than to desalinate seawater and use it for irrigation, is likely to have a lower water and carbon footprint [38,39]. This means that any comprehensive analysis should include the externalities associated with providing, processing and transporting these resources from elsewhere.

Finally, a crucial driver of pressure on food security is political instability. Violent conflicts cause higher food prices and often compromise the production and trade of food [40]. Furthermore they cause severe damage to infrastructure, undermining access to food and creating malnutrition and famines [41,42]. In turn, food insecurity is linked to increased risk of democratic failure and civil conflict. This vicious cycle has been defined a "conflict trap" [26].

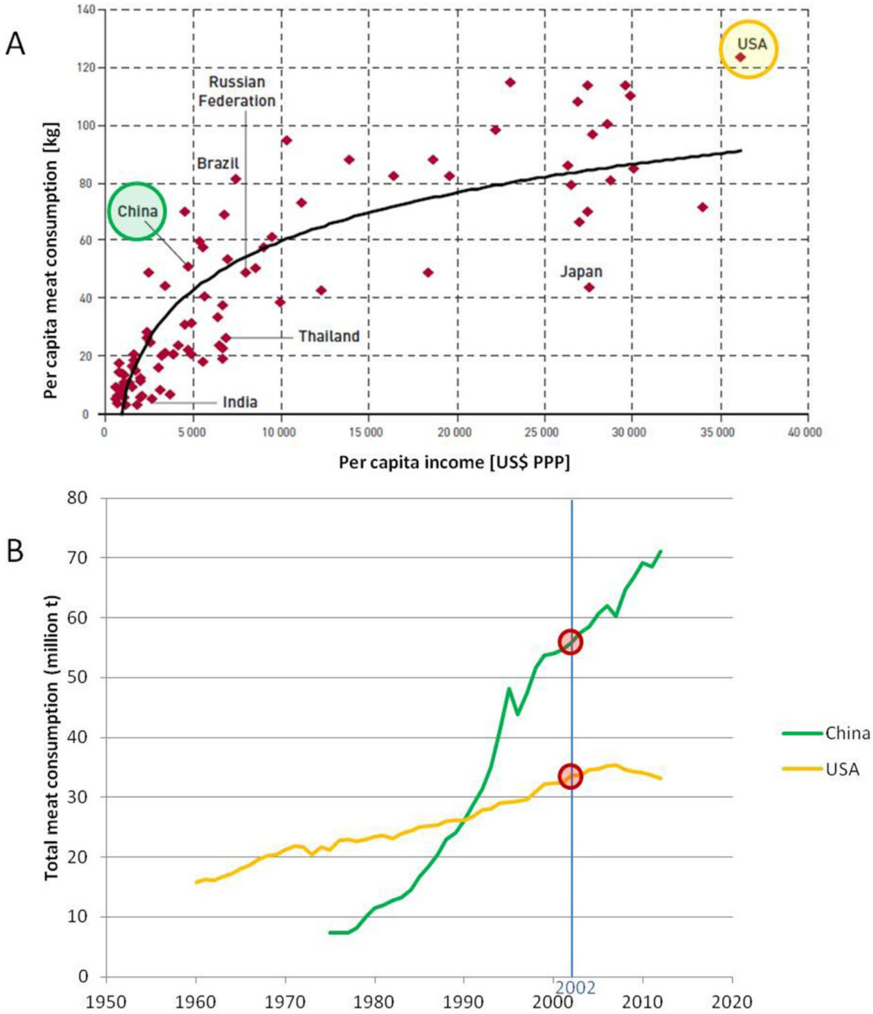

Figure 4. A comparison between per capita and total meat consumption in China and in the USA in 2002. (**A**) The relationship between meat consumption and per capita income in 2002 (Adapted from [43]); (**B**) Meat consumption in China and the United States 1960–2012 [44] .

4. Stage 2: Identifying Key Pathways to Achieve Food Security with EWFN.

Several challenges can be found throughout literature relating to the concept of food security [6,7,45]. These can be grouped into two main challenges or goals:

- Sustainably balancing the growing demand for food with supply streams
- Ensuring universal access to food, nutritional security and stability through time

Given that both are extremely ambitious and multidisciplinary, this paper focuses mainly on the first goal, as its achievement is a necessary condition for achieving the second. Furthermore, it is within this challenge that most of the potential benefits of having a Nexus approach lie. As analyzed in Stage 1, the aim of balancing the demand for food with supply streams can only be achieved if all the resources involved in food production and the impact on the environment of production processes are taken into consideration in one integrated way. Numerous pathways have been suggested to reach this primary goal that seek to sustainably manage and mitigate for the contributions that a food system makes to climate change whilst developing food production methods that replenish rather than deplete biodiversity and related ecosystems [6–8,46]. These include:

- Pathway 1—Employing sustainable production methods [7,47–50] (Section 4.1)
- Pathway 2—Changing diets [6,7,24,49,51] (Section 4.2)
- Pathway 3—Reducing wastage [6,7,49,52–56] (Section 4.3)

This three-pathways approach is now analyzed and their connection with the nexus approach underlined.

4.1. Pathway 1: Employing Sustainable Production Methods

There is common agreement that:

> *"More food will have to be produced at a lower environmental cost in a resource constrained environment."*
>
> ([7,57])

In terms of water resource availability, in 2000, 10 countries used more than 40% of their water resources for irrigation, and were therefore defined as suffering critical water scarcity [27]. On top of over consumption of water, a threat is presented by salinization and pollution of water courses and bodies and degradation of water related ecosystems [58]. This is not the only resource whose limited availability is critical for increasing agricultural production. For example allied to this is phosphorus, which is used in the production of chemical fertilizers. (The price of phosphate rock increased by 700% in 14 months between 2007 and 2008 [59]). Another typology of chemical fertilizers are nitrogen based, the main criticality associated to them is the highly energy intensive process associated to industrial nitrogen fixation (in the US 70% of greenhouse gas emissions in corn production are related to nitrogen fertilizer [60]. Furthermore, excessive use of chemical fertilizers can cause water pollution through runoff. As emphasized by the FAO, which conducted a project assessing land degradation at a global level [61], land represents another critical resource. Stiff competition ensues for its use as a consequence of other human activities (like urbanization and cultivation of crops for biofuels) and where land is available it may no longer be productive because of unsustainable land management (which leads to desertification, salinization, soil erosion and other consequences) or simply because land banks that must exist for the protection of biodiversity and ecosystems services (such as carbon storage) must be given priority [6,20,62,63].

It is, therefore, extremely important to optimize the use of inputs in agricultural production. The EWFN approach can assist in such aim through informing policies and regulations that promote the implementation of more efficient production technologies. Some examples are solutions for water conservation (like rainwater harvesting) and efficient water use technologies (on time water delivery and micro irrigation), increased fertilizer use efficiency (through more precise application of fertilizers, nitrogen fixing, use of compost), increased yields to input ratio, and reduced carbon intensity of fuel inputs (by using alternative sources for energy production such as wind and solar power or anaerobic digestion) [6,19,51]. Notwithstanding these requirements, existing policies created with a silo approach have traditionally focussed only on food security, while heavily subsidising water and energy requirements for food production. These are explicitly in conflict, dis-incentivizing farmers to invest in new technologies [10].

4.2. Pathway 2: Changing Diets

About one third of the global cereal production is fed directly to animals [64]. Even though the efficiency of the conversion of feedstock into animal matter is considerably variable among different species (e.g., in developed countries the cereal necessary to have a weight increase of one kilogram is approximately: 7 kg for cattle, 4 kg for pork and 2 kg for chicken [65]), in most cases meat consumption represents a sub-optimal use of land, water and energy resources involved in the agricultural production [6,51]. In addition, according to the FAO's *Livestock Long Shadow* report [43] and many other LCA analyses [66–69], livestock has a strong impact on water pollution, land use and biodiversity, and heavily contributes to greenhouse gases emissions (contributing to 18% of global emissions over its lifecycle [43]).

Amongst studies aiming at identifying dietary patterns that have a lower impact on the environment, the great majority agrees on the benefits of reducing meat consumption [70–77]. Often this argument has been supported by health reasons, asserting that a shift towards a more plant based diet would improve health, as proven by a number of dietary guidelines promoting a lower meat consumption compared to the current one in western countries [78–80]. However, taking the attitude that meat rearing and consumption is always negative is over simplistic: in developing countries meat represents an important source of some vitamins and minerals which are crucial for children's development [81,82].

There is a vast range of literature that focused on finding synergies between a shift towards healthier diets and environmentally friendly ones, some examples are [72,83–89]. However, it has been discussed that this might not always be the case, for instance Macdiarmid *et al.* [87] discussed some examples of tradeoffs between health and the environment such as fish intake and low fat diary and lean meat. Others have discussed a number of parallel solutions for dietary shifts that would lower our impact on the environment such as: the consumption of seasonal products [90], seeking a balance between energy intake and expenditure [76] and a lower consumption of products such as coffee, tea, cocoa and alcohol that usually come with a high environmental burden and are not necessary from a nutritional perspective [72].

The benefits that a EWFN approach brings to this discussion is that it serves to emphasize the importance of considering embedded water and energy inputs (and carbon outputs) in food production when supporting and guiding a shift towards less intensive consumption dietary choices. Such a mentality stands behind the application of a range of methodologies (such as LCA, water footprinting, carbon footprinting etc) that can quantitatively assess the performance on diets. The results of those studies can be used to facilitate transparently informed consumers choices.

As an example, an app has been developed by the Dutch organization *Varkens in Nood*, which enables purchasers to scan a product and obtain information on its environmental impact (obtained through the application of LCA) and to receive suggestions for similar products which have a better score [66]. Such innovations are an integral part of a nexus approach.

4.3. Pathway 3: Reducing Wastage

It has been estimated that throughout the global food chain approximately 30% of food produced for human consumption is lost or wasted [56,62]. The stages of the food system that experience most wastage can vary significantly when comparing developing and developed countries. In developing countries most of the food loss occurs in the field (as a consequence of pests and pathogens [91]) and at post-harvest stages, as a consequence of poor infrastructure, technical limitations in harvesting techniques, storage and cooling technologies, packaging and lack of connection to markets [56]. Differently, in the developed world most of the waste occurs at the retail, food service and household level. A study conducted by WRAP [92] estimated that in the UK household food waste corresponds to one third of the amount of food purchased, similarly in the US the level of food waste has been estimated up to 40% of food purchased [93]. There are many reasons for this: low prices of food, which encourage wasteful behaviors; extreme reliance on "use by" dates, which often underestimate the shelf life of the product for safety reasons; aesthetic criteria as a result of which retailers throw away perfectly edible fruits and vegetables; offers, which encourage consumers to buy more than they can consume; and oversized portions proposed by the food service sector [6,55,56,92,94].

The impact of food waste and losses on the environment, in terms of the resources involved in the production, processing, transport and consumption stages was highlighted by the FAO in its Food Wastage Footprint report [62], in which for the first time the impact of food wastage on climate change, biodiversity, water and land was assessed at a global level. Figures 5 and 6 extracted from this report, illustrate the impact on climate change deriving from food wasted at each phase of the supply chain, highlighting how the later in the supply chain food is wasted, the higher the impact will be, due to the accumulating impacts of the previous phases.

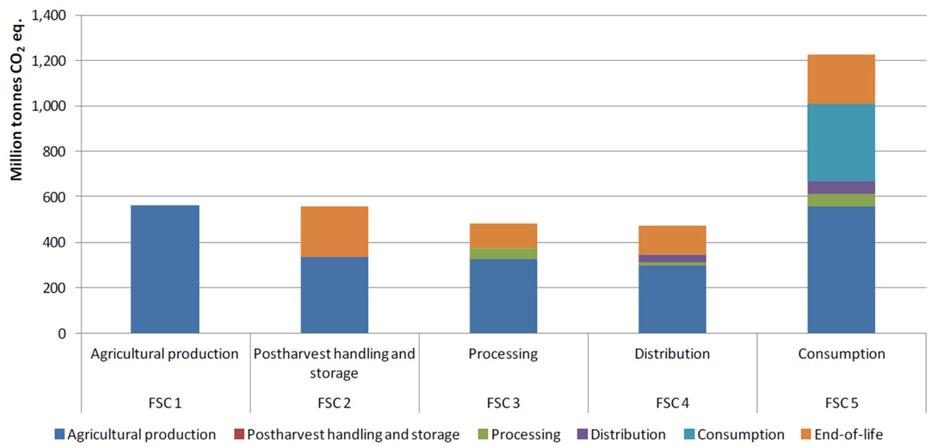

Figure 5. Carbon footprint of food wastage, by phase of the food supply chain with respective contribution of embedded life cycle phases [62].

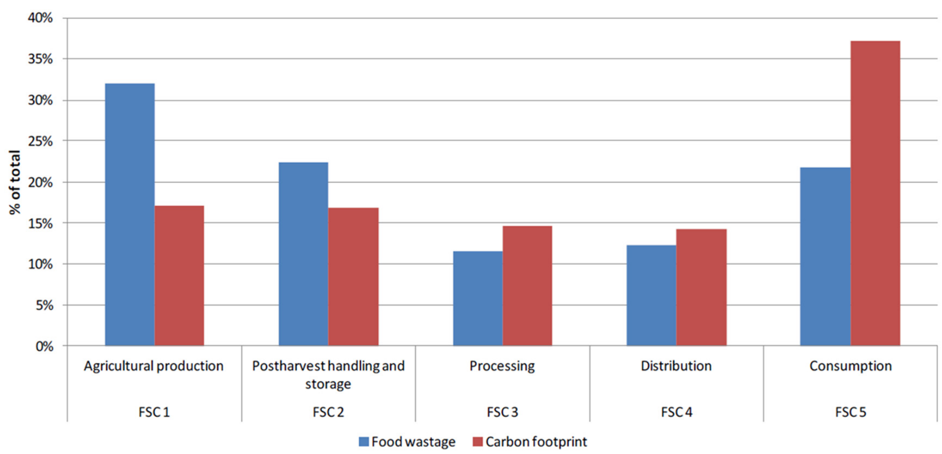

Figure 6. Contribution of each phase of the food supply chain to food wastage and carbon footprint [62].

Similarly, in a study by Kummu *et al.* [52], it was assessed that the production of lost and wasted food crops accounts for 24% of total freshwater used in food crop production, 23% of total global cropland area and global fertilizer use. As pointed out by the UNEP [95], food wastage not only represents an inefficient use of resources and ecosystem services, but also a large source of methane emissions at the landfill stage.

If the current minimum loss and waste percentages in each food supply chain step was to be applied everywhere, approximately half of the food supply losses could be saved, and therefore their associated resources [52]. It is, therefore, clear that the application of a EWFN approach can be crucial in serving to underline the opportunity for improving overall resource efficiency offered by reducing wastage (in terms of food, energy and water) at all stages within the food chain [24,62,96] and can foster productive recycling of food no longer fit for consumption as animal feed or as a source of energy [7].

5. Stage 3: EWFN: The Role of Life Cycle Assessment in Applying a EWFN Approach to Food Security

In order to approach the EWFN it is necessary to develop methods of analysis that can supply information on the complex relationships between water, energy and food [12,97]. Amongst the existing methodologies, this review focused on Life Cycle Assessment for reasons discussed in the following paragraphs.

5.1. Definition of LCA and Its Historical Development as a Tool Applied within the Agri-Food Sector

Life Cycle Assessment (LCA) is a tool to assess the potential environmental impacts, such as the use of resources and the consequences of releases, throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal [98]. The term "product" includes both goods and services. The "life cycle thinking" approach differentiates this tool from other environmental management approaches and enables users to better consider problem shifting—in other words, movement of resources from one phase of the life cycle to another or geographically from one place to another [99]. Another aspect of uniqueness is that the environmental impacts are assessed through a wide range of environmental indicators, which avoids shifting from one environmental problem to another [100,101].

LCA is considered to be a major tool to guide a shift towards sustainable food systems [11] for primarily two reasons: by enabling the identification of where the main impacts lie in the life cycle of a product, it points to where the introduction of alternative operations would be more effective; and, since it presents clear numerical results, it enables users to dismantle common sense assumptions, such as *food miles*, and create information to guide consumers' choices [24]. Figure 7 shows that within the last decade there has been a steady increase in the number of journal articles where LCA has been applied to the agri-food sector (Blue indicators). The other three series of indicators refer to a selection of the above publications that respectively are aligned with pathways 1, 2 and 3 identified in Section 4. A predominance of publications focusing on production methods can be seen, this will be further discussed in Section 6.

The use of LCA in the agri-food sector has gained momentum in the last two decades because of an increased awareness on the pressures posed by food production and consumption on the environment [102–104]. The first "International Conference on LCA in the Agri-Food Sector" was held in 1996 in Brussels, and, since then, eight other editions have taken place, the last in 2014, bringing together the world experts in this interdisciplinary research field, which includes agronomic, food and nutrition science and environmental system analysis disciplines [11].

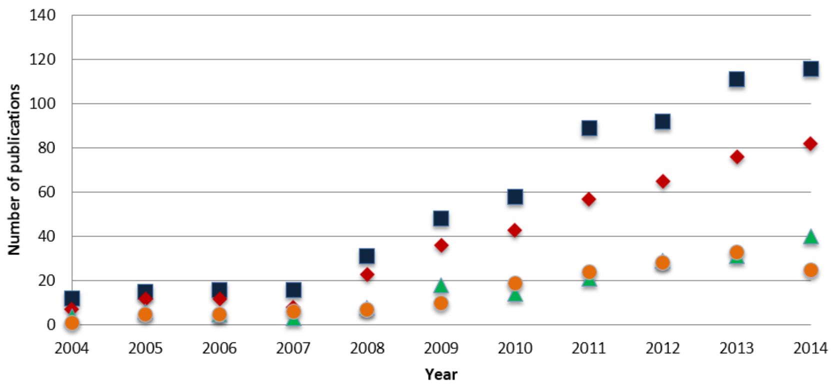

Figure 7. Number of peer reviewed articles published between 2004 and 2014 related to LCA and food. These results came from Scopus when using "LCA" OR "Life Cycle Assessment" AND "Food" as "Title, abstract, keywords" respectively, and subsequently refining the search adding the words "Production", "Consumption" and "Waste".

5.2. Categorizing Applications of LCA within the Food Sector

The literature base identified in Section 5.1 was interrogated in order to identify how LCA had been applied, which stakeholders were involved and how these mapped onto the three pathways identified in Section 4. The database consisted of publications presented where:

- The study is the result of applying the LCA methodology to a product/group of products in the agri-food sector.
- System boundaries must include the production stage (*i.e.*, cradle to farm gate, cradle to retail, cradle to plate and cradle to grave).
- The study must have been published in a peer-reviewed scientific journal or in the proceedings of the last edition of the LCA & Food conference [105].

This resulted in the identification of five different applications of LCA considering five overarching goals. The relevance to the three pathways is shown in Table 1 and discussed here.

5.2.1. Pathway 1—Employing Sustainable Production Methods—Type A

LCA has been extensively used as both a decision making and a learning tool (which can potentially lead to decision making) [106]. Studies Type A, which assess the environmental impact of a product through its life cycle and identify "hot spots" (*i.e.*, potential areas for improvement), can fall in both categories. The system boundaries are from cradle to farm gate, or cradle to factory gate (in the case of processed food items). The functional unit adopted is usually mass based (e.g., 1 kg of beef cattle live weight at farm gate [100]).

The results of these types of study, which are aligned with aspirational shifts towards more sustainable production processes, can lead to the creation of Environmental Product Declaration (EPD), defined as Type III environmental declarations by the ISO 14025 [107]. As explained in this standard, potential applications of EPDs are:

- Influence Green Public Procurement
- Product development (Ecodesign) and improvement
- Business-to-consumer communication

Furthermore LCA studies have created the evidence to inform a number of environmental policies that aim at increasing the resource efficiency and lower the environmental impacts of current food production methods (e.g., the *Roadmap to a Resource Efficient Europe* [108]), or reports that inform policy [31,33,109].

Table 1. Grouping of LCA literature according to five overarching goals.

Type (of Application)	References	Pathway	Applicable Instruments	Stakeholders
A—Assessment of the environmental impact of production processes and products	[100,110–125]	1: Employing sustainable production methods	Environmental Product Declarations (ISO 14025)	Public procurers, producers, consumers, food service providers, policy makers
			Regulations and fiscal measures to foster resource efficient production	
B—Comparison of alternative consumption choices (products/meals) for communication purposes	[66,71,90,102,116,126–135]	2: Changing diets	Information/education campaigns	Consumers, food service providers, policy makers, third sector (e.g., Sustain[136])
C—Assessment of the environmental performance of diets	[63,70,72–76,84–86,88,89,130, 137,138]		Fiscal measures to influence consumers' choices	
D—Assessment of potential environmental savings of food wastage reduction	[132,139–147]	3: Reducing waste	Awareness raising campaigns	Consumers, third sector (e.g., WRAP[148])
			Fiscal measures (incentivizing redistribution and increasing levies on landfill)	Policy makers, producers, retailers, food service provides
			Quality standards revision	
E—Investigation of the role of packaging in food waste reduction	[149–156]		Packaging innovation	Producers, policy makers
			Regulations on packaging	

5.2.2. Pathway 2—Changing Diets—Type B and C

Amongst studies where LCA is applied with the purpose of fostering a shift towards more sustainable consumption patterns, two main groups were identified.

Type B studies compare alternative consumption choices such as products or full meals (e.g., a traditional burger *versus* a vegetarian one, or a seasonal *versus* a non-seasonal raspberry, see [71] and [90]). As products are analysed at consumption stage the system boundaries are usually from cradle to plate including the distribution and retail stages, and in some cases from cradle to grave, including the end-of-life stage (household waste management) and the functional unit is usually mass based (e.g., 800 g of sliced bread at consumption stage [116]).

Whilst sharing the same overarching aim, Type C studies are conducted at a different scale, as they are focused on the assessment of the environmental performance of overall diets, usually comparing a set of diets with a baseline scenario, as in Saxe, Larsen and Mogensen [72]. System boundaries and functional unit are usually the same as in the previous two groups (Types A and B) as these studies often use secondary data from LCA studies of food products and meals as a starting point.

The results of both types of studies can be used in communication and education campaigns to increase the awareness of consumers of the impact of their choices on the environment. Examples of this are: the *Double Pyramid*, a communication tool developed in Italy that aims at promoting a Mediterranean diet (Figure 8), the *Livewell* plate, which was developed in the UK with the purpose of meeting at the same time dietary requirements and the 2020 target reduction in greenhouse gases emissions [87] and the *Meat Guide*, a consumer guide using a traffic light system to assist consumers in making less environmentally harmful meat choices [157]. Furthermore, such studies can inform policy interventions that aim at favoring certain dietary choices, such as fiscal measures, as suggested by Wirsenius *et al.* [158].

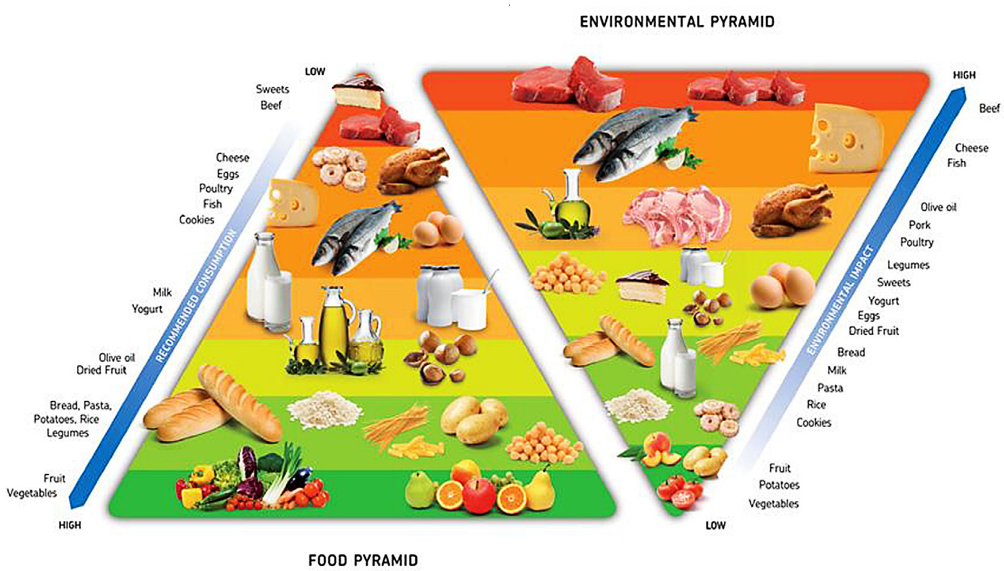

Figure 8. Double Pyramid: a communication tool developed by the Barilla Centre for Food and Nutrition [159]. (Reprinted figure with permission from BFCN. The double pyramid. Source: http://www.barillacfn.com/en/bcfn4you/la-doppia-piramide/. Copyright (2016) by Fondazione Barilla Center for Food & Nutrition.)

5.2.3. Pathway 3—Reducing Waste—Type D and E

Two main groups were identified in the literature for studies that share the aim of fostering a reduction in food waste. In both cases the functional unit is mass based and the system boundaries are from cradle to grave (e.g., 1 kg of potato waste at household level [141]).

In Type D studies LCA is applied to the full life cycle of a waste product, or a group of products, with the purpose of quantifying the potential environmental savings that would have occurred if that waste had been avoided. This can lead to the development of campaigns that aim at raising awareness on the environmental burden of food waste (for example the *Love Food Hate Waste* program conducted by WRAP in the UK [160]). Additionally LCA studies can provide the evidence base to put in place a number of policy instruments for tackling the problem of food wastage. Some examples are: incentives for redistribution to farmers, food manufacturers, retailers and the food service sector, increased levies on bio-waste sent to landfill and the revision of quality standards that lead to the wastage of significant amounts of products for aesthetic reasons[62].

Type E studies centre on the role of packaging on food waste, where LCA is used to analyse trade-offs between employing packaging solutions that have a higher environmental impact but foster food waste reduction. Such studies can influence food manufacturers in developing improved types of packaging (e.g., active packaging [153]) and policy makers to stipulate or update regulations on packaging and packaging waste [161].

6. Discussion

This paper identified three pathways to tackle food security: employing sustainable production methods, changing diets and reducing waste. All three foster the potential for making more efficient use of resources involved in food system activities combined with a reduction in their impact on the environment. A nexus mentality using the EWFN approach, which involves thinking of resource streams/flows of energy, water, land and food in an interconnected way with the overarching aim of improving the overall efficiency of the food system, is therefore implicit.

In the last decades, LCA has emerged as a dominant methodological framework in the assessment of the environmental impacts of consumer products thanks to its holistic and comprehensive approach, as it accounts for all stages of the life cycle of a product, thereby avoiding "problem shifting", and specifically because it takes into account the globalization of the food supply chain [101,103,162]. Through the provision of clear numerical results LCA studies can provide the evidence base necessary to foster beneficial change in terms of production methods (pathway 1—through assessing the impact of production methods and technologies), consumption patterns (pathway 2—through the comparison of alternative products that can enable the identification of those that are most resource intensive and guide consumers towards more sustainable food choices and diets) and food wastage reduction at all levels (both at production and consumption stage, pathway 3). Such a view is supported by publications that have shown how LCA can be applied as a tool for either decision making, learning or communication.

Historically, food related LCA studies have been conducted with the scope of identifying opportunities to improve the environmental efficiency in food production [103] (feeding into what Garnett [8] defined the *efficiency orientated* perspective). For this reason, and for the intrinsic high data intensiveness of the LCA tool, most of the literature applying LCA to the agri-food sector is either aimed at assessing the environmental performance of one single product or comparing a small number of similar products, either with a focus on the production method (Type A) or for evaluating alternatives, to inform consumers' choices (Type B). The remaining uses (Types C, D and E) appear to be less recurrent through literature and include studies that are generally based on secondary data originating from study Types A and B (as in Williams and Wikström [149] and Scholz, Eriksson and Strid [139]). These applications of LCA therefore represent areas where little research has been conducted thus far, leaving space for explorative future research work to be undertaken.

Works belonging to Type C, which aims at assessing the environmental performance of one or more diets, is highly data intensive, and more often than not results in a methodological approach that is less rigorous than traditional LCA. For instance, results are presented for fewer impact categories and these most commonly include global warming potential, land use and energy use, or the analysis simply does not sufficiently take account of specific production conditions in different countries, for example see the work by Saxe, Larsen and Mogensen [72]. The same can be said for studies assessing the environmental impact of wastage produced on a large scale (for example in the retail sector or at a national scale as in Scholz, Eriksson and Strid [139] and Eberle and Fels [140]), which requires a considerable amount of information and therefore simplifications have been made.

A further application of LCA that has an impact on all of the three pathways, and has yet to be sufficiently well adopted, is an environmental performance assessment of food service providers, in terms of menu choices, procurement choices, waste production and management. Very few examples of this type of study were found in the literature [67,163–165], which creates potential research opportunities both in relation to the private and the public food service sectors. One such requirement must surely be with respect to the creation of a uniform certification scheme, which would enable direct comparisons to be made between different restaurants' environmental performance. In the same way, the public food sector (schools, hospitals, universities, care homes, *etc.*), with its tremendous potential for influencing a shift towards more sustainable practices, both amongst producers (through green procurement) and consumers (thanks to its nudging power), is an area of study where the application of a robust methodology, such as LCA, within a EWFN approach can ensure that the most effective efficiency measures are applied and the correct information on sustainable food choices is delivered at the right time. Crucially, it would also result in the dismantling of "common sense myths" on sustainable food.

7. Conclusions

This paper argues the need to find a balance between a growing demand for food and the planet's limited capacity to support its production as a necessary step to achieve food security. The solutions therefore need to focus both on the production side of the equation and on the consumption side, which is argued to be often overlooked [166]. A water, energy and food nexus (EWFN) mentality can support this endeavor by identifying synergies and trade-offs between water and energy systems and food systems, and therefore opportunities for efficient resource use and reduced environmental impact both in food production practices and consumption choices. Such an approach can be enabled by applying an EWFN approach to food systems using the Life Cycle Assessment (LCA) tool, in which the quantitative environmental assessment of a product over its life cycle will provide valuable information for decision making, education and communication purposes. From the review of LCA studies conducted, it appears that the majority of studies undertaken have been orientated towards assessing the resource efficiency and environmental impact of current food production methods, whilst fewer are focused on assessing the environmental performance of diets and the potential environmental savings of food wastage reduction. Of particular interest, and one area scarcely represented in the literature, is the potential of LCA in assessing the performance of food service providers, which can lead to the identification of improvement measures in line with the promotion of the described shifts in both production and consumption patterns.

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